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SCENARIOS FOR THE ROLES OF HYDROGEN IN A FUTURE ENERGY SYSTEM BASED ON RENEWABLE ENERGY

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Abstract

An all-renewable energy system for a group of North-European countries is investigated by temporal simulation of the demand-supply matching for various system configurations. The role of hydrogen technologies for energy storage and fuel cell applications is studied and applied to both stationary and transportation sectors. It is shown that there is scope for considerable amounts of energy trade between the countries, due to the different endowment of different countries with particular renewable energy sources, and to the particular benefit that intermittent energy sources such as wind and solar can derive from exchange of power. A smooth energy supply is demonstrated by use of the seasonal reservoir-based hydro components in the northern parts of the region. Comments are also made on the competition between biofuels and hydrogen in the transportation sector.

1. Introduction

The possibility of supplying all energy needs in society from renewable resources was first proposed by Sørensen [1]. That study constituted the first use of the scenario technique to the energy sector, and was one of the first demonstrations of the role that hydrogen can play as an energy carrier and storage medium. Other suggestions of an important role for hydrogen in future energy systems were put forward during the early 1970ies, e.g. by Marchetti [2], Bockris [3] and Veziroglu [4], but mostly based on supply from non-renewable resources such as nuclear energy.

Over the following decades, increasingly more detailed modelling of the functionality and consistency of such energy systems were carried out. Recent examples are [5-8]. The present study is part of an ongoing project on the relationship between hydrogen and energy trade [9], aiming at studying the roles of energy trade and large-scale hydrogen storage in an all renewable energy-hydrogen energy system for Denmark and the neighbouring countries with which energy trade is already established (Norway, Sweden, Finland and Germany).

A number of energy demand scenarios have been formulated, based on the central assumption that the energy conversion technology used in 2060 with have an average efficiency at least as good as the best commercially available technology serving the same purpose today. For many technologies, the cost of the best technology is not distinguishable from that of average or poor efficiency alternatives. One may consider a dedicated further investment in high efficiency and still remain below the cost of producing the unit of energy saved by the efficiency measure. Folded with the efficiency improvement is the development in energy-consuming services demanded. Such demand has in periods been increasing fairly rapidly (more dwelling floor space per person, more transport work per person per year, more energy-using gadgets, etc.), although there are also areas of diminishing energy use. Out of a range of demand scenarios considered for the project mentioned above, I use a middle one for the present study. The energy demand assumed in 2060 for Sweden is shown in Figure 1. For the other countries, the demand per capita is similar, with variations due to different intensity of industry and different climatic conditions for building heat losses.

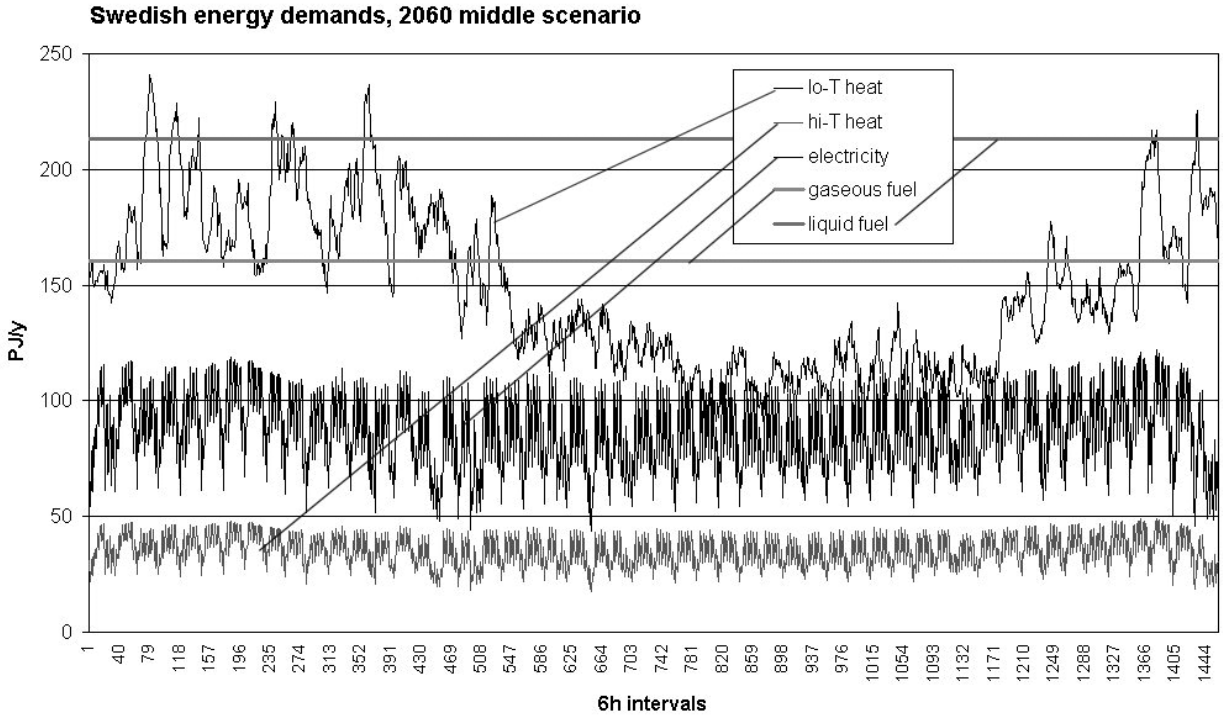

Figure 1. Energy demands for Sweden used in the 2060 scenario. The electricity usage shown is dedicated electricity, implying that further electricity may also be used to cover other needs, if convenient. The energy delivered for transportation is divided equally between fuel cell vehicles using hydrogen ("gaseous fuel") and biofuel vehicles (using "liquid fuel" such as biodiesel, ethanol or methanol), but the energy demand is different due to different engine efficiencies.

The primary energy sources are wind power (on- and off-shore) for regions with a fairly open coastline, hydropower for regions with suitable mountains and biofuels for the regions with either agricultural or forestry production. Only residues from these activities are considered for energy purposes, in order not to interfere with food production or alter forest coverage. However, aquaculture in near-shore locations is considered, as this is seen as an important potential source for biofuels in the future. Whether a competition with food production over such off-shore areas will emerge depends on the global population growth, but even so, one could again restrict the energy use of biomass to the residues from food production. Finally, solar energy used for electricity or heat production is considered for the southern part of the region under study (i.e. Germany), because further north, the seasonal mismatch between solar radiation and energy demand (especially for space heating) is likely to make solar solutions remain too expensive. Small contributions to solar hot-water production in summer and other sources such as geothermal have been omitted because their contribution is likely to remain small, even 50 years into the future.

The energy sources that could be employed in a sustainable way and with acceptable social and environmental impacts are summarised in Table 1. The wind potential on land is derived from re-analysis data ensuring measurement consistency by use of global circulation modelling [10], and assuming a wind turbine density similar to the one presently existing in Denmark, but using contemporary multi-megawatt units. The wind potential off-shore is estimated from satellite scatterometer data [11, 12], and the area fractions of near-shore waters employed are similar to those already set aside for wind power purposes in Danish waters. Biomass potentials are estimated from global vegetation growth models [13, 7]. The hydro figures are the current actual production [14], as no expansion is foreseen, and finally, the solar radiation and collector model used for Germany is described in [7]. It assumes photovoltaic collectors with an average efficiency of 14%, but with removal of useful thermal heat from the same collectors at an average efficiency of 36%. The combined heat and power panels are denoted “PVT collectors”.

Table 1. Potential renewable energy supply considered for use in the North-European countries considered (unit PJ/y). PVT is combined photovoltaic and thermal collectors.

Country:	DK	N	S	SF	D
Wind on-shore	64	167	201	147	157
Wind off-shore	358	974	579	391	177
Biofuel from agriculture	241	51	111	49	1993
Biofuels from forestry	58	523	1670	1180	892
Biofuels from aquaculture	153	223	320	205	108
Hydro	-	510	263	49	27
Solar PVT electricity	-	-	-	-	129
Solar PVT heat	-	-	-	-	275

2. Simulation method

A number of one-year time simulations were made for possible future energy systems combining the data series (using a 6 hour time step) for supply and demand as discussed above, and with use of different sets of conversion devices with different orders of priority. One set of simulations assumed half the transportation activities to use fuel cell-battery hybrid vehicles and the other half Diesel or Otto engines in vehicles of high basic efficiency. Hydrogen is stored in underground caverns such as aquifers or salt dome intrusions and piped to filing stations [8, 15]. Power transmission lines within and between the countries were assumed to be upgraded as necessary. Biofuels can be used at arbitrary pace, while solar and wind energy must be used as produced.

The energy form initially produced was either electricity, liquid fuels or heat. A priority schedule then first allocated bound or available production to simultaneous demands, then considered using stored energy for unsatisfied demands and finally considered energy transformation from one form to another, so that additional demands could be covered. Heat was divided into low-temperature (under 90°C) and high-temperature (over 90°C) heat, the latter being supplied by converting electricity or fuels and the former by associated heat from power-producing fuel cells or other power plants or boilers, and else by heat pumps using electric power at a coefficient of performance around 4 (using soil or water streams as low-temperature reservoirs). Hydrogen was produced by fuel cells in reverse mode of operation, or by electrolysers (which are also fuels cells, but of alkali type as opposed to the membrane types currently appearing most promising for automotive purposes).

A second set of simulations assumed that viable fuel cells would not become available, putting more strain on the biofuels for use in the transportation sector. Hydrogen could still be used for storage, but due to the large amounts of hydropower based on seasonal reservoirs in the region, this turned out to be unnecessary.

The simulations were first performed for each country alone, identifying export potentials and import requirements, both in the form of a time series. A second round of simulations were then performed, using the identified surpluses as import options for those countries with unsatisfied demands.

3. Simulation results

The Nordic countries are characterised by generous access to renewable energy: Large amounts of hydropower in Norway and Sweden, large amounts of wood scrap from forestry operations in Sweden and Finland (to be converted to e.g. methanol in the scenarios) and large amounts of wind energy along coastal sites in all of the four countries (plus the 5th Nordic country, Iceland, which is not included here because it has no grid connections to the other countries). It is therefore not surprising, that the simulations show that these countries can be self-sufficient in energy supply from such renewable sources. It is perhaps surprising, that the intermittency of wind energy is not so large, that any substantial trade of electric power between the Nordic countries is called for. Figure 2 shows some uses of wind power in Denmark, for the scenario with fuel cells and geological hydrogen storage.

It is seen, that the number of hours where wind cannot cover the direct electricity demand is quite low. The same is true for coverage of heat demands by electric furnaces (high-temperature heat) and by heat pumps (low-temperature heat). The hours of deficit are in all cases covered by conventional combined heat and power plants using biofuels. Indeed, the availability of Danish biofuels (associated with residues from a large agricultural sector) would allow all needs in the transportation sector to be covered. Alternatively, hydrogen may be generated from excess wind (and here the occasional deficits do not matter, since hydrogen may be stored in the underground caverns) and used in the transportation sector, leaving more biofuels to be exported to countries with less abundant renewable energy supply. The situation is similar for the other Nordic countries, with large amounts of wind power and biofuels potentially available for export. Also here, half of the energy for transportation is assumed derived from hydrogen, and Figure 3 shows the role of a moderate size store placed in Finland (the capacity of 1.37 PJ is assumed for hydrogen stores in each of the Nordic countries). The smoothing function of the store is seen to be modest, and the role of the store is really to insure against unusually long periods without wind energy for producing hydrogen for vehicles. The alternative of producing hydrogen from biomass is not included in the present scenarios.

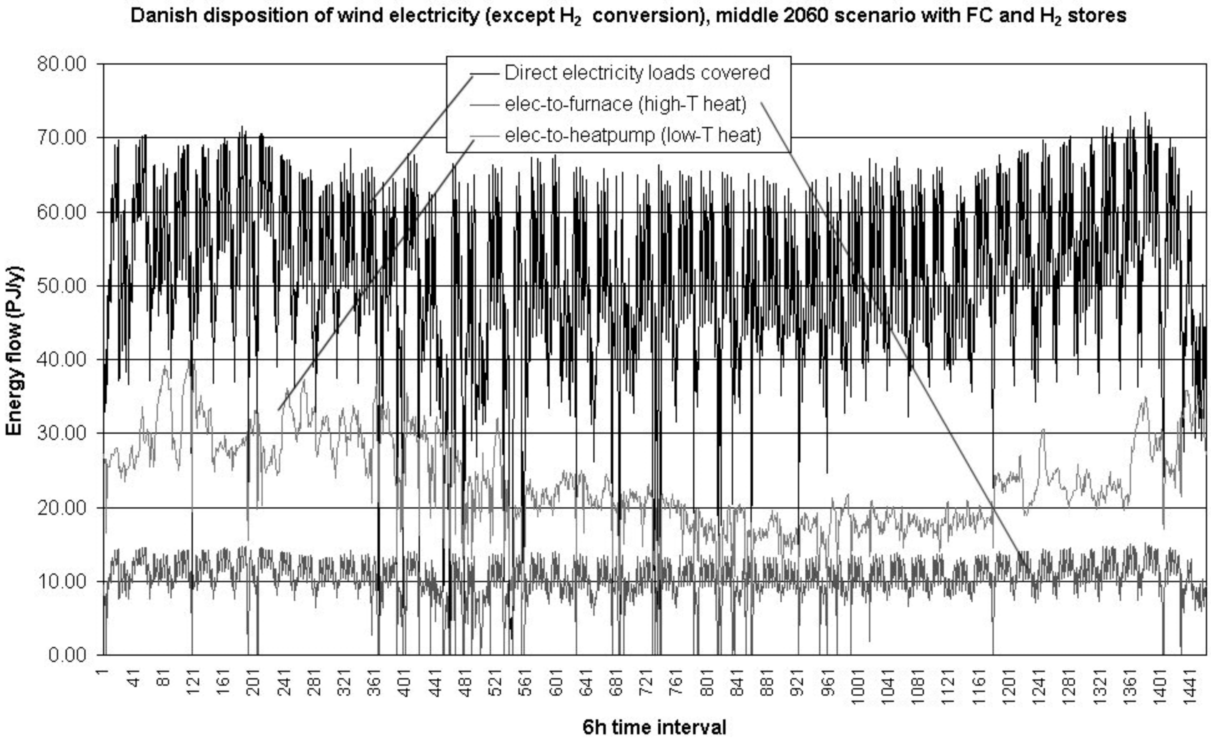

Figure 2. Disposition of wind power generated in the 2060 scenario for Denmark. Not shown is wind power used for hydrogen production (163 PJ/y).

Finally, the situation for Germany is interesting, as the renewable resources are here considerably more modest: very little hydro, suitable wind power locations only at the northern coasts (Baltic and North Sea), and some solar energy derivable from building-integrated panels. Biofuels are more abundant, based primarily on residues from a sizeable agricultural sector. Forestry is more modest, and aquaculture limited by the small coastline (although inland waterways may be used to some extent).

As a consequence, it is difficult to secure enough renewable energy for a population more than 4 times as large as that of the Nordic countries, on a land area considerably smaller. Yet, the simulation results show that demand for electricity and heat for both space conditioning and processes can indeed be covered, but only about half of the demand for transportation energy. This is illustrated in Figure 4, which shows the deficit or surplus of biofuels and power that could be used for

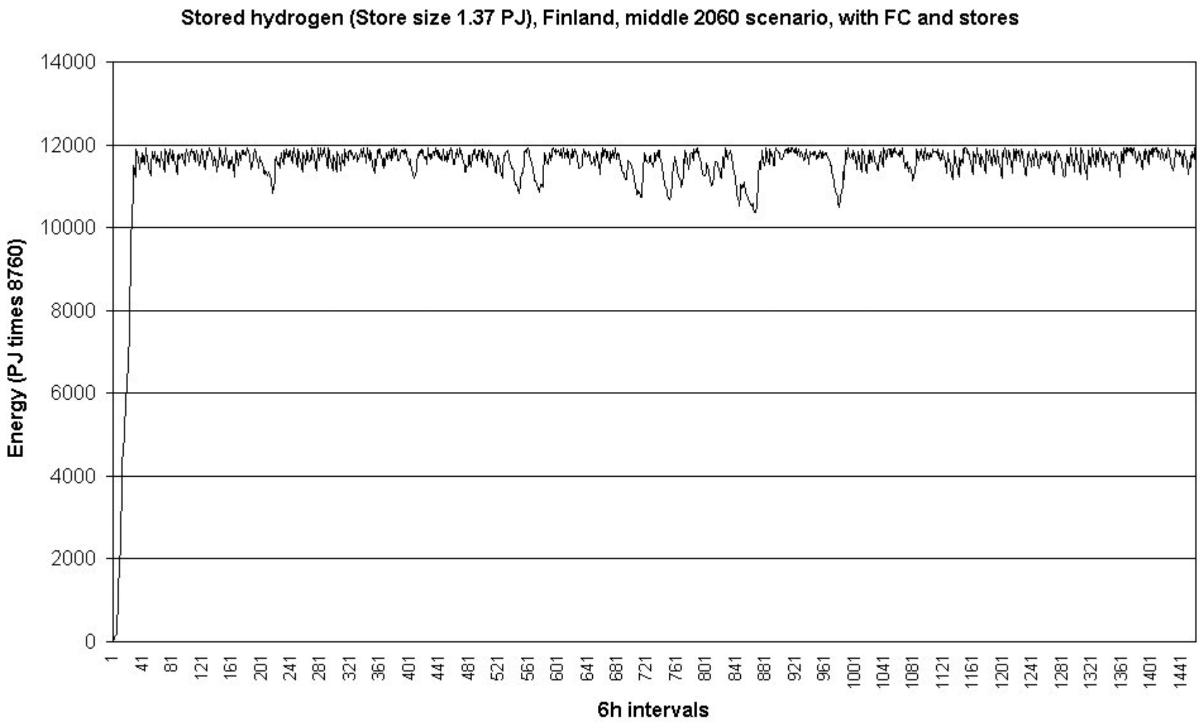

Figure 3. Filling of hydrogen store in Finland, over the simulation year.

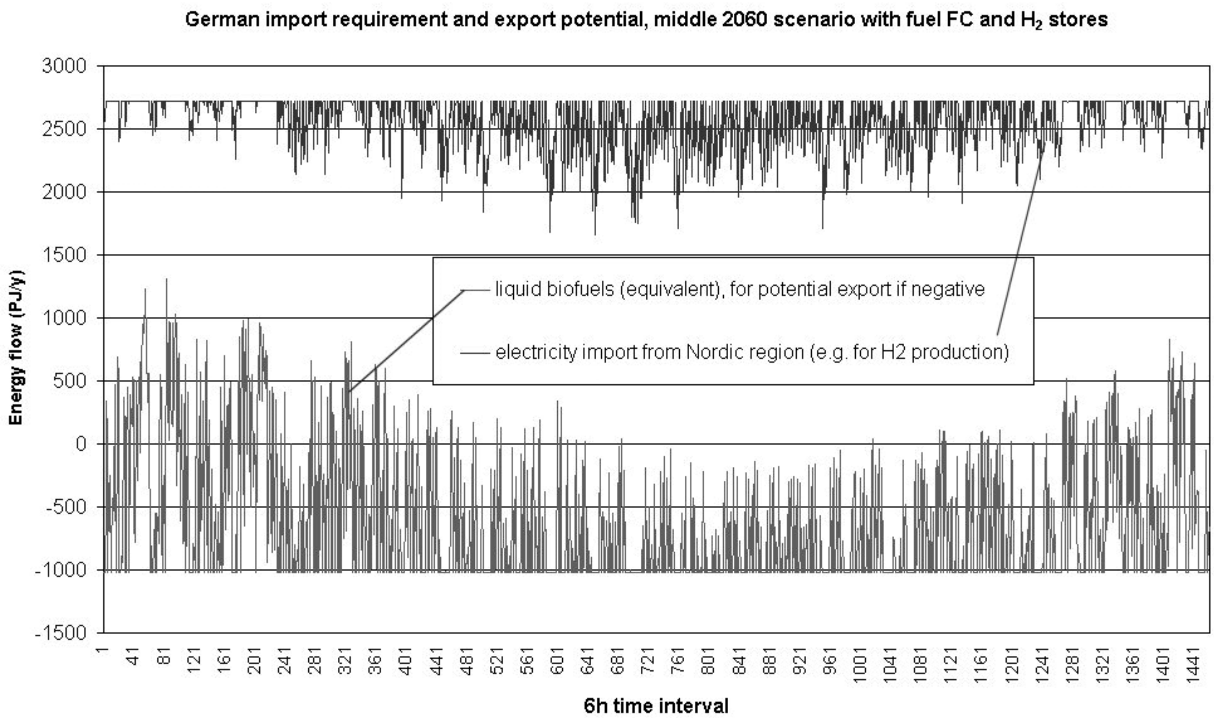

Figure 4. Import needs and export options for Germany in the 2060 scenario.

producing hydrogen for fuel cell-based vehicles. For biofuels, there is a surplus integrated over the simulation year, but insufficient to cover the need in the transportation sector (a little over 50% can be covered at the assumed 26% efficiency of advanced internal combustion vehicles). The apparent need for import during a few hours during winter appearing in Figure 4 is not real, as it is relative to a uniform rate of using biofuels. Since biofuels can be stored, they can also be used at a variable rate as seen required. The remaining energy demand in the transportation sector must be covered by imports. These could be imports of biofuels, for which there is a surplus in the Nordic countries, but the scenario presented rather chooses to use fuel cell vehicles powered by hydrogen produced in Germany using reversed fuel cell operation (which can achieve a high efficiency, cf. Sørensen, 2005), based in imported electricity. The average electricity surplus from the Nordic countries combined is some 2700 PJ/y, and it is seen that Germany needs to import nearly all of this to achieve the hydrogen production required.

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